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1 Integration of upward-GPR and Water Content Reflectometry 2 to monitor snow properties

3

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11

12 **Abstract**

13 We adopt upward Ground Penetrating Radar (up-GPR) and Water Content
14 Reflectometry (WCR) sensors to monitor the seasonal behavior of snow density.
15 Up-GPR permitted to observe at a single fixed station the time lapse response of
16 the electromagnetic signal at the main frequency of 1500 MHz, with the antenna
17 radiating upward from the soil toward the snow surface. Measurements have been
18 performed in a test site on Italian Alps (at elevation of about 2100 m a.s.l.)
19 during the winter season 2014–15 at interval of 30 min. The data processing of
20 radar data involved the traveltime picking and the conversion into snow depth
21 and density. WCR measurements have been useful in order to calibrate the radar
22 response and to retrieve information on the presence of liquid water content.

23 The integration of up-GPR and WCR technology allow us to infer snow high and
24 layering, snow density changes during the winter season and a preliminary
25 estimate of the liquid water content (LWC). For snow in dry condition, we are able to
26 estimate density values through mixing-rules or polynomial formula. Snow density varies during
27 the season in a range between 250-450 kg/m³; the results are in good agreement with the results of
28 the ground-truth. For snow in wet condition, the residuals of the electrical permittivity, after a trend
29 removal on the original WCR data permitted to estimate a liquid water content in the range between
30 3-5 %, during some periods of the winter season, according to warmer climate condition.

31 Snow layering and densification processes are monitored by the response of up-GPR: fast
32 phenomena such as wetting front infiltration can be also pointed out even if they appear challenging
33 if other observation are not available (e.g. monitoring with WCR).

34 **Key-words:**

35 Ground Penetrating Radar, Water Content Reflectometry, Snow density, Snow water
36 content

37

38 **Introduction**

39 The development of non-invasive methods to monitor the density and water content
40 by means of electromagnetic devices is of great interest, because of their
41 capability to operate in complex logistical condition (slopes, remote areas,
42 extreme weather condition,...). Moreover, the detection and monitoring of the
43 mechanical properties, jointly with the liquid water content, are relevant in
44 the analysis of snow-gliding phenomena. Glide-snow avalanches occur when the
45 entire snowpack glides over the ground until an avalanche releases. Snow gliding
46 processes and glide-snow avalanches are mainly caused when a reduction in
47 friction at the base of the snow cover occur (e.g. Schweizer et al. 2003); this
48 phenomena is related to an increase of liquid water.

49 Measurement techniques for the liquid water content of snow are well developed
50 and based on the electromagnetic properties, such as Time-domain Reflectometry,
51 Water Content Reflectometry and Ground Penetrating Radar (Koh et al., 1996).
52 Other methods require an open snow pit and thus are destructive.

53 The electromagnetic properties of snow are relevant because of their sensitivity
54 to density (e.g. Godio and Rege, 2015a, Godio, 2016) and liquid water content
55 (LWC) changes. Moreover, water percolation in snow or the presence of a wet
56 basal layer in the snow cover are potentially (e.g. Godio and Rege, 2015)

57 associated to the triggering of avalanche and local instability phenomena.

58 Time-domain reflectometry (TDR) allows for non-invasive continuous monitoring of
59 snow properties within the snowpack (e.g. Schneebeli and others, 1998). Water
60 Content Reflectometry (WCR) is based on similar technology of TDR (e.g. Stein,
61 1997) and can be easily adapted for automatic monitoring of electromagnetic
62 properties of snow (e.g. Godio et al. 2015b).

63 Ground Penetrating Radar (GPR) is a promising technology for many applications
64 in snow science, and quantitative results on snow stratigraphy based on radar
65 signals referring on the temporal evolution at a specific site, are of great
66 interest in risk avalanche prediction. Ground Penetrating Radar (GPR) is widely
67 adopted to detect the snow depth and snow-water equivalent (e.g. Godio, 2008,
68 Rege and Godio, 2012, Prevati et al. 2011, Forte et al. 2013). The method
69 provides an accurate estimate of the snow depth with much less time spent in the
70 field compared to conventional measurements (e.g. Godio and Rege, 2016, Bruland
71 et al., 2000). Pulsed and frequency modulated GPRs are promising methods, even
72 if they require great care in data processing and calibration as the snow depth
73 is estimated from the traveltime of the radar signal. GPR survey is suitable to
74 cover large areas in an accurate and fast way (e.g. Marchand and al. 2001).

75 The upward Ground Penetrating Radar (up-GPR) is herein adopted to monitor in
76 time lapse modality the snow properties using a single antenna, disposed on the
77 soil and radiating upward (on the snowpack). Up-ward looking GPR is not a
78 novelty in snow monitoring (e.g. Heilig et al, 2009, 2010, Schmid et al., 2014),
79 while TDR and WCR are widely adopted for soil moisture and they can be

80 successfully adopted to estimate and monitor electrical permittivity of snow
81 (e.g. Prevati et al. 2011). Otherwise, the integration of GPR and WCR allows us
82 to monitor the time-lapse behavior of snowpack during the winter season by an
83 integrated approach, where WCR data are useful to calibrate the GPR response.
84 We have installed upward-looking GPR with the objective of continuously
85 monitoring the temporal evolution of the seasonal alpine snowpack and deriving
86 snow stratigraphy information from the radar signals. The radar response is here
87 analyzed according to the analysis of the WCR data. Particularly, we focus on
88 determining the snow height, the amount of new snow, snow settlements and liquid
89 water content.

90

91 **Materials and Methods**

92 The monitoring of snow properties was performed at the flat-field test site of
93 Sant'Anna, located above Gressoney at 2100 m a.s.l. in the Monte Rosa sky resort
94 area. The area is on the foothill of the glaciers of Monte Rosa massif in the
95 Western Italian Alps.

96 The equipment has been installed in the test site in September, in order to have
97 enough time to calibrate all the devices before the beginning of the winter
98 season (Figure 1).

99 Particularly the test site was addressed with one up-Ward GPR, with an antenna
100 working at the main frequency of 1500 MHz; the antenna was buried within the
101 soil (see the paragraph on GPR) and the radar cable was protected and sealed
102 within a corrugated pipe in order to avoid damages due to snow load and possible

103 interferences due to liquid water. The radar unit was installed within a plastic
104 box (together with an external battery), and fixed on a vertical rod, inserted
105 into the ground. The power supply for GPR and other electronic devices
106 (datalogger, WCR units, sensors) was guaranteed by two buffer batteries connected to an
107 inverter and powered by a photovoltaic panel

108 Three WCR probes for estimating (locally) the dielectric permittivity of ground and snow were
109 connected to a datalogger unit by means of coaxial cables (protected by corrugate pipe). One probe
110 was installed directly into the ground; two probes were located at different elevation with respect to
111 the ground level in order to detect the properties of the snow. The datalogger unit was located in the
112 same plastic box of the GPR unit and powered by the inverter-photovoltaic power system.

113 Moreover, the test site was equipped with sensors to record meteorological and
114 snow-cover properties; we have installed snow height sensors (HS), an
115 ultrasonic gauges and air temperature, and snow temperature. The HS sensors are
116 based on ultrasonic devices which measure the traveltime of an high frequency
117 pulse, as described in a following paragraph. The sensors were located at an
118 elevation of about 2.5 meters above the ground, as depicted in pictures of
119 Figure 2.

120 The WCR and GPR measurements were performed in the winter season 2014–15.
121 Particularly, the data acquisition refers to the period starting from November
122 to April, with some lack in data because of some malfunctioning of the GPR
123 equipment.

124 Conventional manual snow profiles according to the methodology suggested by
125 Fierz and others (2009) were conducted on a bi-weekly basis close to the test
126 site. Snow density was determined by taking samples of volume of 100 cm^3 at

127 different depth in a snow pit and weighting them on an electronic scale. For
128 each layer recorded in the snow pit, at least two density samples were taken and
129 averaged (Table 1).

130

131 *Electromagnetic properties of snow*

132 The snow is considered as a continuous mixture in which the ice and vapor
133 constituents are themselves treated as individual but interacting continua. Snow
134 on the ground is viewed as an un-saturated three-phase granular material
135 comprised of small grains of ice with interstitial pores partially filled by a
136 single vapor. A small fraction (less than 10 % in volume) of porous voids can be
137 filled by liquid water (wet snow). Bradford et al. (2009) provided an overview
138 on the effect of liquid water content on the electrical permittivity of snow;
139 Lundberg and Thunehed (2000) considered the effect of liquid water on the radar
140 signal into the snowpack. Otherwise, the electrical permittivity of dry snow and
141 ice at different temperature and density has been widely reported (e.g. Evans,
142 1965, Glen and Paren, 1975). In such condition (dry snow), the electromagnetic
143 measurements can be easily and accurately converted into snow density.
144 Particularly GPR survey is suitable to detect snow depth and dielectric
145 permittivity with high resolution, until a depth of several meters (e.g.
146 Previati et al., 2011).

147 Mixing rules or adapted mixtures rules relate the dielectric permittivity of the
148 mixture with permittivity and fraction of volume of each single phase. For dry
149 snow (two-phases), several relationships between the electrical permittivity and
150 snow density are well established (e.g. Looyenga, 1965), while for wet snow,

151 where a small fraction of liquid water provides a marked increase of electrical
152 permittivity of the mixtures, the relationships are more challenging, because of
153 the complexity to distinguish between the effect of changes of snow density from
154 liquid content on the observed dielectric permittivity.

155 The radar performances in terms of reflectivity, vertical resolution and
156 penetration depth have been widely discussed in literature (e.g. Godio, 2007,
157 2009, Prevati et al., 2011). From an electrical point of view, the dry-snow can
158 be considered as non-conducting medium; the electromagnetic wave does not suffer
159 of the intrinsic attenuation as it propagates through the snowpack and it can be
160 assimilated to a lossless medium, in such a case, the complex permittivity is
161 equal to the real permittivity. For instance a granular snow at high density
162 ($>600 \text{ kg m}^{-3}$) is characterized by a wavelength of 0.2 m (at 1 GHz) and a
163 theoretical vertical resolution of 0.05 m (assuming the vertical resolution
164 equal to 1/4 of the wavelength).

165 At the interface between two snow layers or between the snowpack and the air,
166 considering a normal plane wave incidence, the reflection (Γ) and transmission
167 coefficient (τ) are:

168

169
$$\Gamma = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1}$$

170

171
$$\tau = \frac{2\eta_2}{\eta_2 + \eta_1}$$

172

173 where η is the intrinsic impedance (Ohm m) of layers 1 and 2.

174 When a signal meets a thin snow layer, multiple reflections between the two
175 interfaces limiting this layer could arise. The amplitude of the resulting wave
176 is dependent on the interferences between the reflected waves, which can be
177 constructive or destructive in function of the traveltime into the layer, itself
178 dependant on the thickness and the snow density.

179 If both geometric and intrinsic attenuations can be neglected, and if the signal
180 is a continuous plane sinusoid, the resulting reflection coefficient ranges
181 between 0 for purely destructive interferences to one or more maxima, for
182 constructive interferences. Considering a thin snow layer (medium 2), embedded
183 into a medium 1, and assuming a thickness (t) of the layer comparable to the
184 wavelength in the first medium, an appropriate expression for the reflection
185 coefficient is (Godio, 2009):

$$186 \quad \Gamma = \frac{\Gamma_{12}(1 - e^{i\beta})}{(1 - \Gamma_{12}^2 e^{i\beta})}$$

187 where

$$188 \quad \beta = \frac{4\pi t}{\lambda_1}$$

189 and λ_1 is the wavelength in the snow layer 1. As the wavelength of the signal is
190 related to the wave velocity, it depends on the density of the snow pack, and
191 therefore the reflection coefficient is affected by the density variation.

192 A detailed description of the relationship between thickness of a thin snow
193 layer and the reflection coefficient at different frequencies is reported in
194 Godio (2009). For a thin high density snow layer ($\varepsilon = 3$) embedded in a softer
195 snow, with a permittivity value equal $\varepsilon = 2$, the trend of reflection coefficient

196 with respect to the frequency is dependent by the thickness of the layer.
197 In the frequency range from 100 MHz up to 2 GHz, the trend can be assumed linear
198 for very thin layers ($t = 5\text{--}10\text{ mm}$). For increasing thickness (e.g. $50\text{--}100\text{ mm}$),
199 the reflection coefficient assumes a sinusoidal behavior with peaks at different
200 frequencies. For instance, a thin layer of 50 mm is characterized by a maximum
201 of reflection coefficient is at 1 GHz . For a thickness of 100 mm , at the
202 reference frequency of 1 GHz , the reflection coefficient is almost null.
203 As far as the amplitude of the reflection coefficient is concerned, at the
204 frequency of 1 GHz , the values vary from 0.25 for a thin layer of 5 mm , to 0.05
205 for the layer of 10 mm and to 0.2 for the layer of 50 mm .

206

207 *Dry snow*

208 For dry snow, a simple relationships between the snow density and the
209 electromagnetic properties yields. The Robin' s equation, for instance, is an
210 empirical relationship between density and electrical permittivity (ϵ) (Kovacs
211 et al. 1995) :

$$212 \quad \epsilon = (1 + 0.845 \cdot \rho)^2 \quad [1]$$

213 where ρ is the specific gravity of firn and ice (with respect to pure ice) and
214 electrical permittivity is the relative value with respect to vacuum
215 (dimensionless).

216 The technical literature report many variants of mixing models to relate the snow density and
217 dielectric permittivity. The Robin's equation is a simple polynomial fitting of the straightforward
218 Looyenga (1965) formula, which has been widely used for a bi-phasic mixture of snow. A
219 comparison of the validity and drawbacks of different mixing rule is out of the scope of the

manuscript, a detailed description of different approaches is well developed in Booth et alii (2013).
We just infer a range of density values, according to the limits of accuracy of the adopted method
(Looyenga, 1965).

In terms of wave velocity (v) the following relationship yields:

$$v = c / (1 + 0.845 \cdot \rho) \quad [\text{m/ns}] \quad [2]$$

where c is the wave velocity in vacuum (here in m/ns). In the velocity range of 0.2 m/ns to 0.24 m/ns the specific gravity almost double (from 0.3 to 0.6).

The relationship between the radar traveltime (twt) and the specific gravity becomes:

$$twt = 2d / c \cdot (1 + 0.845 \cdot \rho) \quad [\text{ns}] \quad [3]$$

where d is the snow depth; finally we estimate the Snow Water Equivalent (SWE) as:

$$SWE = \rho_{ice} / 2 \cdot 0.845 \cdot (c - v) \cdot twt \quad [\text{kg/m}^3 \text{ m}] \quad [4]$$

Wet snow

Relationships between the electromagnetic parameters and snow properties are usually based on mixing rules, where the bulk electrical permittivity depends on the fraction volume of each single phase: ice as solid phase, gas and free water (e.g. Sihvola, et al. 1985). A polynomial relationship (Denoth, 1994) between electrical permittivity, density and water content is here adopted:

$$\epsilon_{snow} = 1 + 1.92 \rho_{snow} + 0.44 \rho_{snow}^2 + 0.187 \theta_w + 0.0045 \theta_w^2 \quad [5]$$

where ϵ_s is the dielectric permittivity of the snow, ρ_{snow} (g/cm^3) and θ_w (%) are density and water content, respectively. For dry-snow (neglecting the water content), the equation [5] is similar to standard formulation, usually adopted to estimate density values of dry snow (Godio, 2009, Godio and Rege, 2015a). The sensitivity of the electrical permittivity to the water

244 content effect is demonstrated by analysing the behaviour of the formula [5].
245 An increase of 3–5 % of liquid content provides a relative increase of the
246 electrical permittivity of more than 20–35 %, as discussed in other papers (e.g.
247 Godio, 2016).
248 When the the water content is negligible in the reference period, we convert the
249 WCR response in density values using formula [1].

250

251 ***WCR data acquisition***

252 Water Content Reflectometer (WCR) measurements are based on a radio-frequency
253 signal (some decades of MHz) traveling along a two/three rod' s probes, acting
254 as a transmission lines, and observing the period of the reflected signal.
255 Particularly, our device consists in an electronic circuit embedded in the probe
256 of two stainless steel rods, 30 cm length, connected to a datalogger. The signal
257 velocity is related to the electromagnetic properties of the embedded material;
258 the electrical permittivity of the material is computed from the observed
259 period.

260 Two WCR sensors were located at elevation + 70 cm (WCR 2) and + 40 cm (WCR 3)
261 above the ground; a third sensor was located 5 cm below the surface to monitor
262 the interaction between the snow pack and soil.

263

264 ***Laboratory calibration of WCR***

265 We measured the WCR' s output in air and de-ionized water at different
266 temperatures, to check the temperature dependence of the electrical

267 permittivity water (Hamelin et al., 1998). The tests were performed in a
268 climatic chamber by monitoring the temperature of the water sample with a
269 thermometer model Fluke S4 I. The frequency-dependence of the constituents of
270 the air and ice is herein neglected as Kelleners et al. (2005) suggested; this
271 is admitted in the bandwidth of approximately 175 MHz of the functioning of the
272 adopted sensor.

273 A correction of the observed WCR period accounts for the temperature effect of
274 water, ice and air components. A polynomial of 2nd degree is used to correct the
275 observed data in the range between 0 and -8 ° C. By considering these effects,
276 the electrical permittivity of water decreases gradually during the freezing
277 phase; at -12 ° C, the (relative) electrical permittivity assumes values close
278 to 3.2; by increasing the temperature, the permittivity slowly decreases up to
279 values of about 3 (at 0 ° C), when the melting is starting. Those values agree
280 with literature data on the electromagnetic response of water below 0 ° C.

281

282 ***GPR data acquisition***

283 The upward Ground Penetrating Radar (up-GPR) is a pulse-type radar with an
284 antenna, at the main frequency of about 1500 MHz, posed on the ground surface
285 and radiating upward on the snow.

286 The basic principle is the same of the conventional GPR adopted from the
287 surface; we use a transmitter antenna and a receiver one in bi-static
288 configuration with offset of few cm. The antennas were buried into the ground at
289 the beginning of the winter season, and they have been disposed in such a way

290 that the radiation of the electromagnetic energy was oriented from the ground
291 up-ward. During the wintertime, the ground and the antenna were covered by the
292 snow pack; therefore, the radiation energy propagates from the ground into the
293 snow.

294 A good compromise between resolution and signal quality and penetration depth,
295 is achieved by using (commercial) antennas in the frequency range between 1 - 2
296 GHz. This range is suitable to operate with good performance up to a snow
297 thickness of about 2-3 meters that has not been reached during the monitored
298 season. In environments with very huge snow accumulation (more than 3 m), the
299 adoption of commercial antennas with lower main frequency, such as 900 MHz, is
300 suggested and offers good performance (e.g. Previati et al. 2011). Snow humidity
301 (moisture content) does not seem an obstacle (at least in that site) because we
302 estimate that a maximum value of less than 10 % in volume of liquid water is
303 filling the pore volume during the melting period. This quantity does not affect
304 the signal quality.

305 Snow temperature affect the accuracy of evaluating dielectric permittivity,
306 because of the dependence of dielectric to temperature below 0° Celsius.

307 This must be considered in further research activity.

308 The system sends a series of pulses every 30 min to get the A-scans and all the
309 traces are gathered to obtain a B-scan, where along the x-axis we indicate the
310 reference time instead of a distance, as in standard acquisition. Because the
311 low attenuation of the electromagnetic waves in the snow, high frequency can be
312 adopted; the installed system operates at the main frequency of 1500 MHz, with a

313 frequency band of approximately 1 GHz.

314 We extend the monitoring period from November 2014 till April 2015; measurements
315 were performed every 30 min, with a stacking of 256 traces, on a window time of
316 50 ns and 1024 sampling for each traces. An analog-to-digital converter of 16
317 bit was adopted. Results were stored in separated files in the internal memory;
318 and then downloaded for subsequent data processing, because of the complexity of
319 handling an effective remote control of the system.

320

321 *Data processing*

322 The flow chart of the integrated data processing of GPR, WCR and other data is
323 depicted in figure 3. Particularly, the standard data processing of B-scan
324 involves the edit and removal of distortions of the main-bang, filtering of low
325 frequency electronic noise with dewow, applying the background removal to
326 minimize the main bang effect and reduce coherent “horizontal” noise, The
327 background removal has been performed by averaging 5 traces and subtract the
328 results from the B-scan.

329 We applied a the gain recover procedure to remove the acquisition gain, to
330 apply a divergence compensation, We didn’ t introduce the correction for the
331 intrinsic attenuation because of the negligible dissipation effect of
332 electromagnetic energy in the snow (low attenuation coefficient). The band-pass
333 filter removes the unwanted energy out the frequency band of 1000 - 2200 MHz;
334 finally a trace stacking was performed to get a single traces every two hours.
335 (stacking of four A-scan).

336

337 *Snow surface picking*

338 We adopt a semi-automatic method, which requires manual interaction according to
339 the following steps:

- 340 • a phase follower algorithm detects the peak of the same half-cycle,
341 following the signals at the equal phase;
- 342 • If two consecutive traces deviated, we checked whether the height of the
343 snow surface changed due to accumulation, settling or melt; this step is
344 performed by comparing the GPR data with the high of snow (HS) given by
345 ultrasonic measurements (in the period of overlap of the two
346 measurements); an rough evaluation on settling and melting phase has been
347 possible thanks to the analysis of temperature data;
- 348 • If none of these changes appeared in the recorded weather data, and
349 deviations in the phase sequence occurred (e.g. while surface crusts were
350 persistent or surface melt happened), we neglected phase reversals;
- 351 • During strong accumulation and melt events, manual picking is necessary to
352 reset the follower to the correct phase.

353 Finally, internal layers were picked in a similar way to the procedure of the
354 semi-automated snow surface picking algorithm.

355

356 *New snow height (NSH)*

357 Ultrasonic sensors are conventional instrument for measuring snow height; they

358 are able to measure the distance to the snow from the surface.
359 Particularly, the ultrasonic level sensors work by the "time of flight"
360 principle (basically like the GPR...) using the speed of sound. The sensor emits
361 a high-frequency pulse, generally in the 20 kHz to 200 kHz range, and then
362 observes the echo at the snow-air interface. The pulse is transmitted in a cone,
363 usually about 6° at the apex. The pulse is reflected at the level surface
364 (snow) back to the sensor, now acting as a receiver and then to the transmitter
365 for signal processing. A correction of the speed of sound because of the
366 temperature is necessary for an accurate estimate of the distance between the
367 transmitter-receiver sensors and the snow surface. Usually an accuracy of about
368 2 % is obtained. Data have been acquired every 30 minutes, and recorded in a
369 data logger. A sketch of the installation of the sensors is reported in figure
370 1.

371 During a snowfall, snow height increases and the load of the new snow provides
372 for the settlement of the underlying layers. In such a case the new snow height
373 is always underestimated, i.e. the amount of new snow cannot be measured
374 automatically.

375 The radar, however, still records the reflection of the old snow surface after
376 it was covered by new snow. Therefore by subtracting the two-way travel time of
377 the reflection of the old snow surface from the time of the new snow surface, a
378 more accurate estimation of the fresh snow height can be performed.

379 The process requires an assumption of the fresh snow density. At the elevation
380 of the test site (above 2 100 m a.s.l.), the density of the new snow is usually

381 in the range of 50–100 kg/m³. The wave velocity is in the range between 0.263 -
382 0.274 m/ns; we calculated the new snow height (NSH) using the following
383 equation:

$$384 \quad \text{NSH} = (\text{Twt}_1 - \text{Twt}_0) * c / 2 (1 + 0.845 \rho)$$

385 where c is the wave velocity in vacuum and ρ is the specific gravity of snow
386 with respect of pure ice (assumed equal to 920 kg/m³), and Twt_1 , and Twt_0 are the
387 traveltimes of the “new” reflection and “old” reflection, respectively.

388 The accuracy in the detection of the NSH depends on the uncertainty in the
389 assumption of snow density and on the accuracy in the picking of the traveltime
390 differences. A conservative estimate assumes the uncertainty in the estimate of
391 traveltime about 0.05 ns. Therefore, the accuracy in the new snow estimate is
392 computed according to the following analysis:

$$393 \quad \Delta \text{NHS} = |\partial \text{NHS} / \partial \text{twt}| \cdot \Delta \text{twt} + |\partial \text{NHS} / \partial \rho| \cdot \Delta \rho$$

$$394 \quad \Delta \text{NHS} = c/2 (1 + 0.845 \rho) \Delta \text{twt} + (0.845 c \text{ dt}) / (2 (1 + 0.845 \rho)^2) \Delta \rho$$

395 where $\text{dt} = \text{Twt}_1 - \text{Twt}_0$, and if the upper and lower boundary are considered:

$$396 \quad \text{NHS}^+ = (\text{dt} + \Delta \text{t}) * c / (2 (1 + 0.845 (\rho - \Delta \rho)))$$

$$397 \quad \text{NHS}^- = (\text{dt} - \Delta \text{t}) * c / (2 (1 + 0.845 (\rho + \Delta \rho)))$$

398 For a gravity value of 0.13 with an uncertainty of 0.025, and assuming a
399 differences of traveltimes of 5 ns, and a interval of 0.5 ns, the fresh snow
400 height results:

$$401 \quad \text{NHS} = 0.68 \pm 0.08 \quad [\text{m}]$$

402 with a relative uncertainty of about 12 %.

403

404 *Processing of WCR data*

405 The densification process is a long term process that could provide gradual
406 variation of the response in time during the season. Therefore abrupt changes
407 (in time) of the WCR response are mainly related to the effect on the dielectric
408 permittivity of the liquid water content in the snow. Particularly, time
409 series of WCR data are processed by separating the short term oscillations of
410 electrical permittivity from the long term ones, adopting a de-trend analysis,
411 as depicted in figure 4. Finally the water content is estimated from the
412 residual data of the electrical permittivity, through formula [5].

413

414 **Results and Discussion**

415 *WCR data*

416 The seasonal response of WCR data is shown in figure 4. WCR 1 refers to the
417 response of the probe into the soil. WCR2 and WCR3 are the probe at elevation of
418 +40 cm and 70 cm above the ground (on the snow); the data processing of observed
419 electromagnetic response involves two steps: i) the analysis of the time
420 series, ii) the conversion of the electrical permittivity into snow density and
421 liquid water content by applying mixing rules.

422 We stress the relevancy of monitoring the ground condition, by observing the
423 water content in the uppermost surface soil. We observed all along the season
424 the presence of high water content (almost close to the saturation) and no
425 frozen phenomenon of the soil: this is of interest both for modeling the

426 thermal regime of the snowpack, and for linking different sliding condition of
427 the snowpack at the interface with the ground.

428 The high frequency oscillations at small amplitude are related to the influence
429 of the diurnal temperature, because the measurements are not compensated by the
430 temperature correction; the effect is more pronounced on the WCR 2 that is
431 closer to the snow-air interface, where the exposure and influence of solar
432 radiation and air temperature is more relevant.

433 Moreover the trend of the data of WCR 2 indicates a marked increase of the
434 electrical permittivity of the uppermost layer of the snow pack; the observed
435 values are similar to the values assumed for ice. In this case, like for the
436 seasonal data, we can't distinguish if the effect on the electrical
437 permittivity is caused by densification processes or because a increase of free
438 water content is occurred. The density values have been computed according to
439 the formula [1]; the relationships allowed us to convert the dielectric
440 permittivity of the WCR data into snow density values. Particularly, we observe
441 how the uppermost layers are characterized all over the season by density in the
442 range between 250–300 kg/m³, while at deeper level, density values are around
443 400–450 kg/m³. Those ranges are in good agreement with the values observed on
444 samples collected at different time in snow-pits (Table 1). For the density
445 range in those ranges, the wave velocity is between 0.22–0.24 m/ns.

446 Figure 5 shows a detail of the electrical permittivity response, observed at
447 sensor WCR2, and the de-trend analysis herein adopted in order to separate
448 short-term and long-term oscillations. The residual are used to estimate the

449 liquid content within the snow pack, according to the procedure aforementioned.

450

451 *GPR data*

452 A general overview of the up-GPR response is depicted in figure 6. We plot the GPR data
453 collected in the period January to April 2015. Unfortunately because of a malfunction of the GPR
454 system some data are missing in February. A qualitative comparison between the GPR data and the
455 measures of snow height collected with the ultrasonic device show a good agreement between the
456 two data sets in terms of estimate of snow accumulation at the ground.

457 GPR image (figure 7) shows the temporal evolution of the snow depth accumulated at soil; an
458 average value of 0.23 m/ns is adopted to convert the traveltimes in to snow elevation on the ground.
459 This value has been computed according to an estimate of the average dielectric permittivity
460 derived from the WCR data; particularly we have observed an average value all over the season of
461 about 1.6 \pm 0.1 (1 Standard Deviation) for the probe WCR 2 and 1.8 \pm 0.1 (1 Standard
462 Deviation) for WCR 3. This yields to an average estimate of the dielectric permittivity of the snow
463 pack of 1.7 \pm 0.2; the wave velocity is therefore in the range of 2.2 m/ns and 2.4 m/ns, or 0.23-
464 \pm 0.1 m/ns. The adopted velocity value corresponds to an average density of 350 kg/m³; this value is
465 consistent with the range of values observed all over the season with locally measurements of snow
466 in snow pit (Table 1).

467 The radar section shows several phenomena, that have been highlighted with caps letters.
468 Particularly letter A refers to an abrupt decrease of the snow height just after the first snowfall in
469 November. This is caused by a marked increase in the average temperature in that period,
470 responsible both for a rapid snow settlement (compaction), both causing the formation of a basal ice
471 crust (letter B) and probably also a rapid melting of the snow pack occurred. Subsequent snow falls
472 (letter C and D) provided for an abrupt increase of the snow height in the day from 9 to 11
473 December. Other snow fall events are pointed out with letter E,F.

474 A sharp increase of reflectivity of the inner features within the snow pack are highlighted with

475 letters B, G and H. Feature B refers to the formation of a basal crust, subsequent to the partial melt
476 and re-frozen of the snow pack at the beginning of December; features G and H are instead located
477 in the uppermost zone of the snow pack, close to air-snow interface. Two different explanations can
478 be given: i) an increase of the humidity of the new snow with respect to the old one provide an
479 increase of the contrast of the electromagnetic properties between new and old snow; ii) the new
480 snow is characterized by very low density, with respect to the older one; this provides an high
481 reflection coefficient between new and old snow but with a reverse sign with respect to the case i).
482 A detailed analysis of the phase behavior could be helpful in better understating the reason of the
483 hot spots of reflectivity is still in progress.

484 We also observe a gradual decrease of the snow depth after the main snowfalls,
485 according to snow settlement because of the thermal or mechanical densification
486 processes. This is well depicted in figure 7 by analyzing the trend of the air-
487 snow interface, for instance in between event E and F and between F and G.

488 We note well separated reflection events into the snowpack; the snow layers that
489 are detectable in the radar image refer to layers with different density values
490 within the snow pack. We can outline the event in between features G and H;
491 pointed out with a dashed black line. This event refers to a reflection of a
492 layers into the snowpack, that shows a gently decrease of the snow-high with
493 time. .

494 Above the snow-air reflection some weaker artifacts can be observed (letter M in figure 7); those
495 artifacts are associated to multiple reflections of the main features (layers) within the snow pack.
496 This is consistent with the similarity of the trend of the artifacts (multiples) and the inner reflectors.
497 The high contrast of dielectric permittivity between the snow pack and the air (2.5 snow, 1 air)
498 explain how some energy can be trapped within the uppermost snow layers, generating the multiple
499 response.

500 The analysis of the behavior at the end of the season (Figure 8) reveals the
501 relationship of radar signal with the gradual snow melting; particularly, this
502 effect started at the beginning of April and can be observed till the end of
503 April. We note the similar high frequency (daily) fluctuations of the radar
504 signal at snow-air interface, that can be also observed in the snow depth
505 (ultrasonic data). This corroborates the assumption of the relationship between
506 the oscillations of the signals and the partial frozen-and melting phase of
507 water within the snow pack. This phenomena provides for slight but detectable
508 (according to the instrumental accuracy) behavior of the expansion and
509 contraction of the snow pack because of different density of the snow pack
510 during the partial-melting phase and during the re-frozen period. The
511 fluctuations are related to the different densities of the two phases of water.

512 Our experiment setup is different from that addressed in similar research activity. For instance
513 Schmid et al. (2015) proposed an interesting combination of up-GPR and Global Positioning
514 System devices to monitor snowpack properties. In particular they installed up-GPR and a low-cost
515 GPS system below the snow cover and observed the evolution during two winter seasons. Applying
516 external snow height (HS) information, they demonstrated as both methods provided consistent
517 liquid water content estimates in snow, based on independent measurements of travel time and
518 attenuation of electromagnetic waves. We obtained similar results by integrating up-GPR with
519 WCR information, even if we focus on density evaluation more than on LWC. Moreover, we focus
520 on the behavior of the ground just below the snow cover and we demonstrate (in this case) that the
521 soil has been, during all the winter season in not frozen condition. This has relevant implication for
522 the analysis of water exchange between the ground and the snow pack and also in the evaluation of
523 thermal regime at the snow-ground interface.

525 *Snow depth and temperature*

526 The analysis of snow depth trend from January to April points out the several
527 precipitation events mostly occurred in March (Figure 9). The climate conditions
528 of the site have been responsible of relevant snow falls, followed by abrupt and
529 marked snow settlements We highlight note the event of February, the 5-6th: an
530 accumulation of about a 40 cm of new snow occurred but the day after an abrupt
531 increase of the air temperature provided for a sudden snow settlement (more than
532 30 cm). This was followed by a few days of stability, with a small reduction of
533 the snow depth (few cm), according to the decrease of the air temperature. This
534 fast snow settlement is also visible in several events in February and March.
535 The snow settlement appears very sensitive to the diurnal fluctuations of the
536 air temperature, and obviously to the general climate conditions. The response
537 is very fast, with relevant consequence to the probability of an increase of
538 free water content in the uppermost layers of the snow. This could be analysed
539 in detail considering the reflectivity and phase of the radar signal, for
540 instance.

541 The snow depth reached a maximum values of about 120 cm and then gradually
542 decreased till less than 60 cm at the end of April. Small fluctuations of snow
543 depth can be observed with a daily frequency. We associate this effect to the
544 melting and refrozen of ice-water in the pore space of the snow, that slightly
545 modifies the snow depth.

546 The snow melting started approximately at the beginning of April; the comparison

547 between the snow depth, collected by ultrasonic measurements, and the air
548 temperature shows the correlation between the average temperature and the snow
549 melting phase. After a last relevant snow fall, occurred during the days April,
550 5–6th, the average temperature raised up to values above 0° Celsius , with
551 diurnal fluctuations between –5 and + 10 Celsius degree.

552

553 ***Soil water content***

554 The response of WCR in the soil shows a regular and almost constant trend all
555 over the monitoring period. Some small fluctuations could be of interest mostly
556 because they appear well related to the fluctuations observed in the data of
557 WCRs located in the snow (e.g. the event at middle of January).

558 We note that the values of about 45–55 % of water content are compatible with
559 the nature of the uppermost part of the soil, characterised by a soil with high
560 porosity and low permeability. Therefore a high water content is observed and
561 the soil remains in almost saturated condition for long time. The early snow
562 falls at the end of November provided for a enough thickness of snow cover to
563 avoid the water within the soil to freeze. This condition of unfrozen soil
564 remains for all the winter season.

565

566 **Final remarks**

567 We have proven that the integration of WCR and GPR response is an effective tool
568 to monitor the seasonal variation of snow properties. For snow in dry condition,
569 we are able to estimate density values through mixing-rules or polynomial

570 formula. The water content is estimated by performing the analysis of the
571 residuals of the electrical permittivity, after a trend removal on the original
572 WCR data.

573 Snow layering within the snow pack, and densification processes are monitored by
574 upward-GPR: fast phenomena such as wetting front infiltration are of relevant
575 interest but they are challenging if evidences coming from other observation are
576 not available (e.g. monitoring with WCR). Even if an accurate analysis of
577 volumetric water content within the snowpack appears still challenging, we will
578 work on the spatial variability. This will require the development of low cost
579 (simplified, e.g. multiplexing devices) radar system must be developed to drive
580 an array of antennas. WCR is (rather) low-cost devices that can be routinely
581 integrated in snow-weathering stations.

582 The integration of WCR and up- GPR offers a good accuracy in monitoring the
583 average values of snow density. Moreover upward GPR, WCR probes and conventional
584 snow depth observations permit detailed analysis of snow deposition, the
585 settlement phase, densification process and melting and frozen phase.

586 The further data processing would focus on the analysis of the observed data
587 with marked variations of snow depth and with an increase of free water within
588 the pore volume of the snow pack. These phenomena, jointly with the analysis of
589 the temperature trend, could be associated to the probability of the occurrence
590 of snow gliding.

591

592 **Acknowledgements**

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594 *Val d'Aosta* - Italy (B 65 G 13000 00 0006).

595

596 **Table 1:** snow depth and density at two different elevation above the ground
597 during the winter 2014–15, observed in pits.
598

Date	17- Dec	21 - Dec	31 - Dec	7 - Jan	28 - Jan	4 - Feb	12 - Feb	18 - Feb	4 - Mar	11 - Mar
Snow Depth [cm]	80	70	65	64	87	99	110	125	132	113
Density at elevation + 0.7 m [kg/m³]	120- 340	200	-	-	200	260	270	300	320	400- 340
Density at elevation + 0.4 m [kg/m³]	340- 420	300- 360	320	400	400	400	270	380	400	400

599

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689

690

691

692 Captions

693 **Figure 1:** sketch of the test site with position of sensors.

694 **Figure 2:** pictures of the test site; a) installation of the equipment; b) winter
695 time at the test site!

696 **Figure 3:** flow chart of the data processing and data integration between GPR and
697 WCR.

698 **Figure 4:** winter season 2014–2015, seasonal behavior of WCR response, a) WCR 1
699 refers to soil water content; b) WCR2 and WCR3 are the probe at elevation of +40
700 cm and 70 cm above the ground (on the snow).

701 **Figure 5:** a) example of de-trend analysis to separate the short term effect and
702 the long term behavior of WCR data; the residuals of the dielectrical
703 permittivity (short term behavior) are related to the effect of the liquid
704 water content.

705 **Figure 6:** a) up-ward GPR response, period January 2015 - April 2015; blank
706 sectors refer to data missing; b) snow depth by ultrasonic measurements (data
707 missing in the period January–February 2015).

708 **Figure 7:** detail of up-ward GPR response in December 2014, letters A refers to
709 an abrupt compaction and or melting of the snow pack; C, D, E, F, refer to the
710 radar response to the new snow falls, features B, G, H are hot spot of
711 reflectivity within the snowpack, N indicates artifact because of multiple
712 reflections. (see the text for further explanations).

713 **Figure 8:** a) detail of up-ward GPR response during April; the reflection vent of
714 air-snow interface show some pulsation; a similar behavior is depicted by the
715 ultrasonic response (snow height), in figure b).

716 **Figure 9:** Air temperature trend and snow depth according to ultrasonic data
717 during the final snow melting (March–April); the air temperature data are
718 filtered with a low pass filter to enhance the diurnal variation of snow.

719

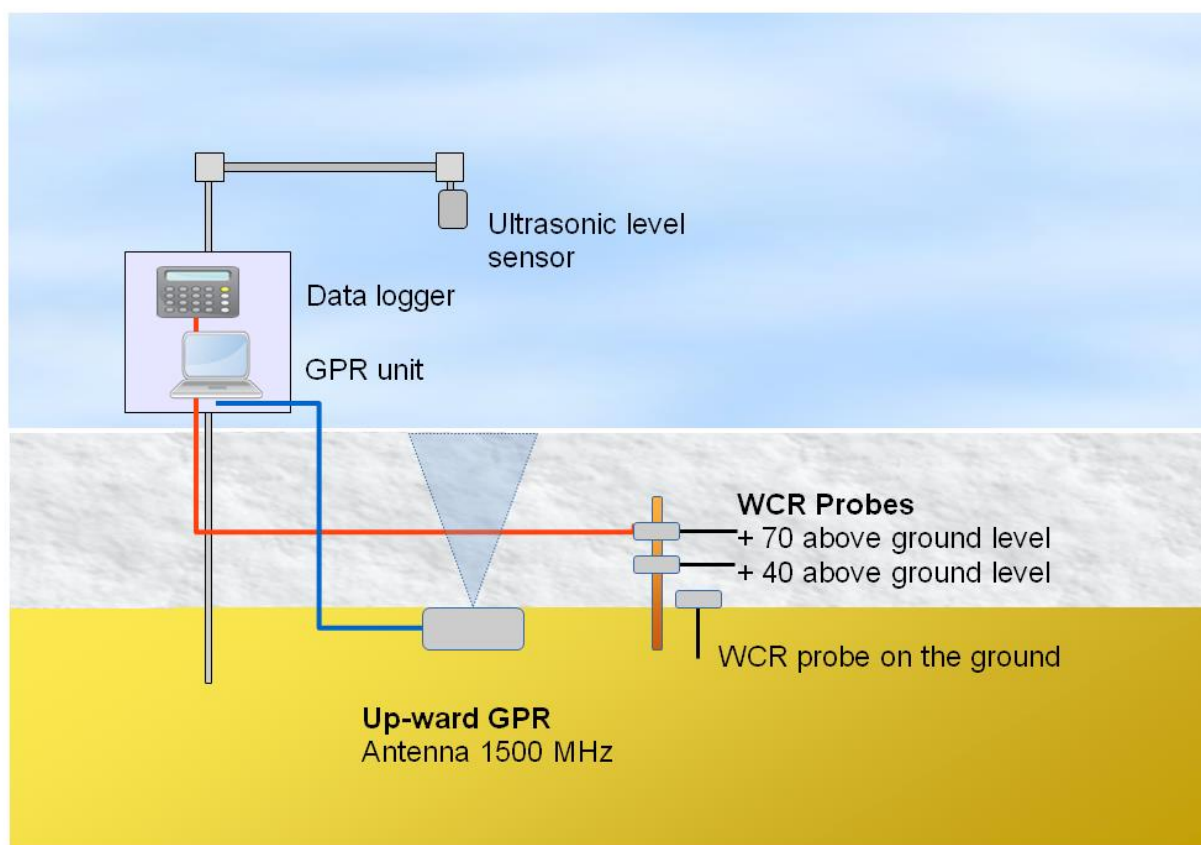
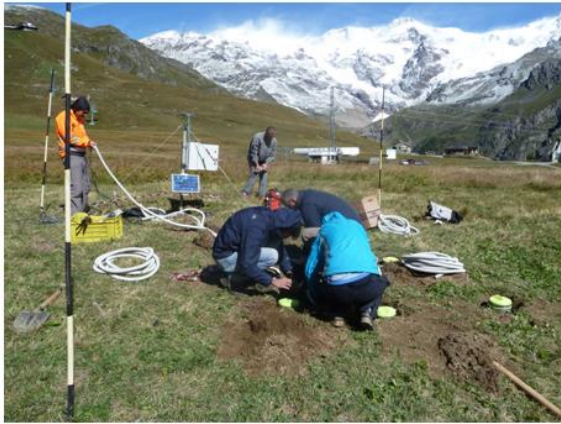
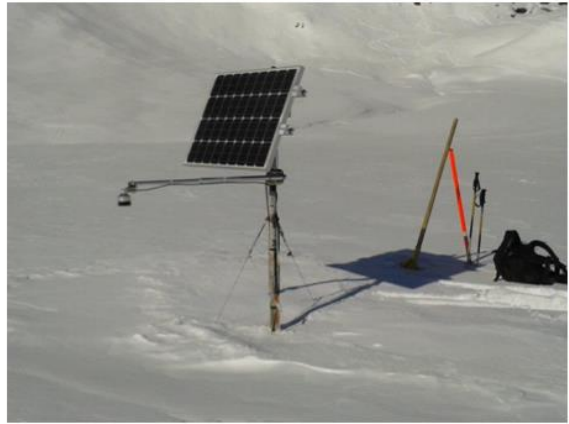


Figure 1

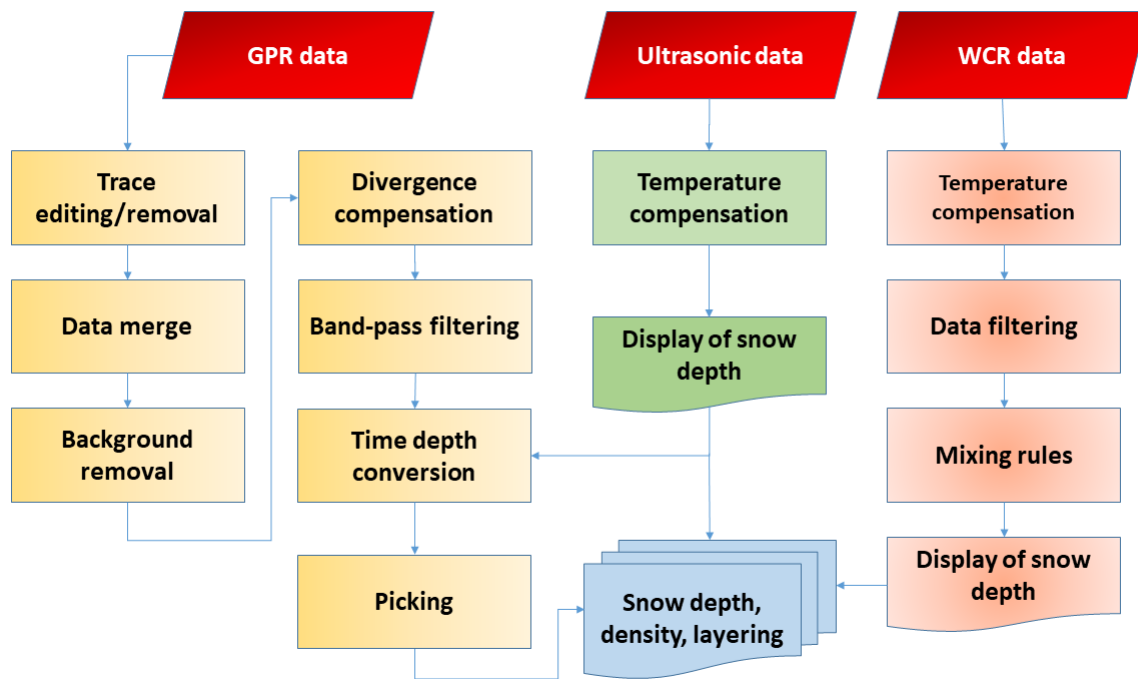


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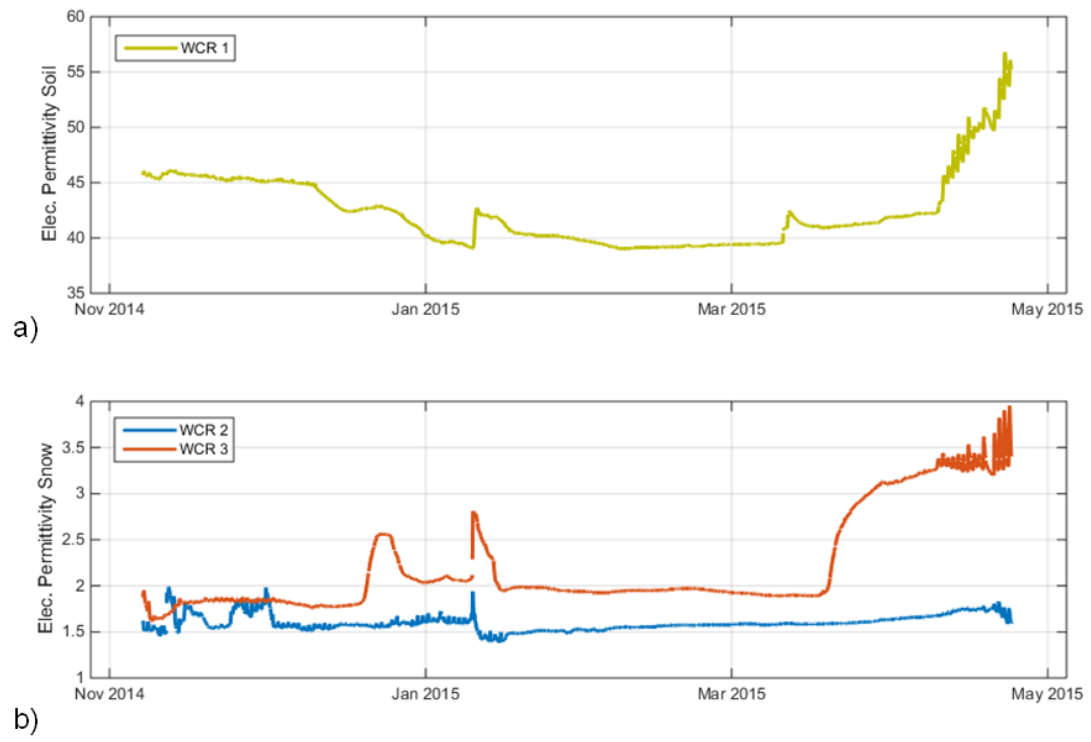


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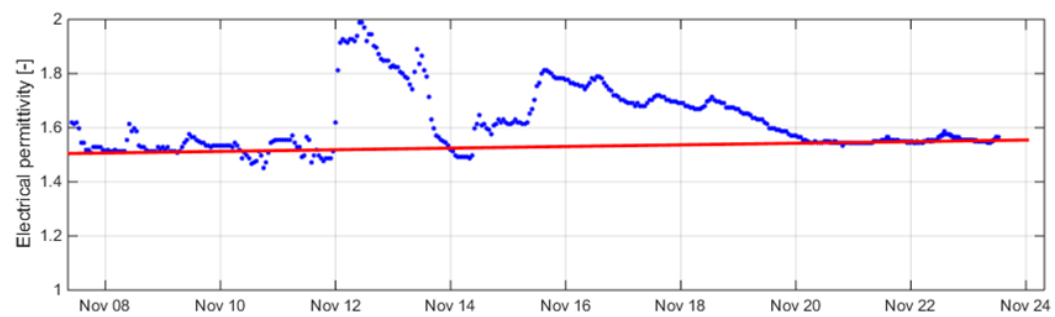
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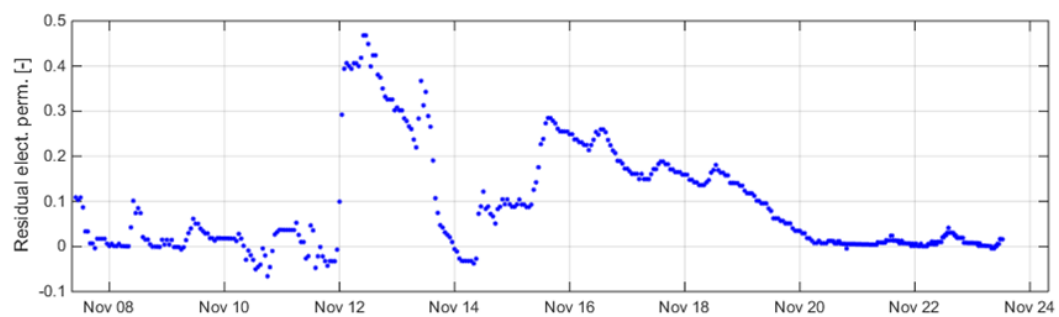
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730 Figure 4
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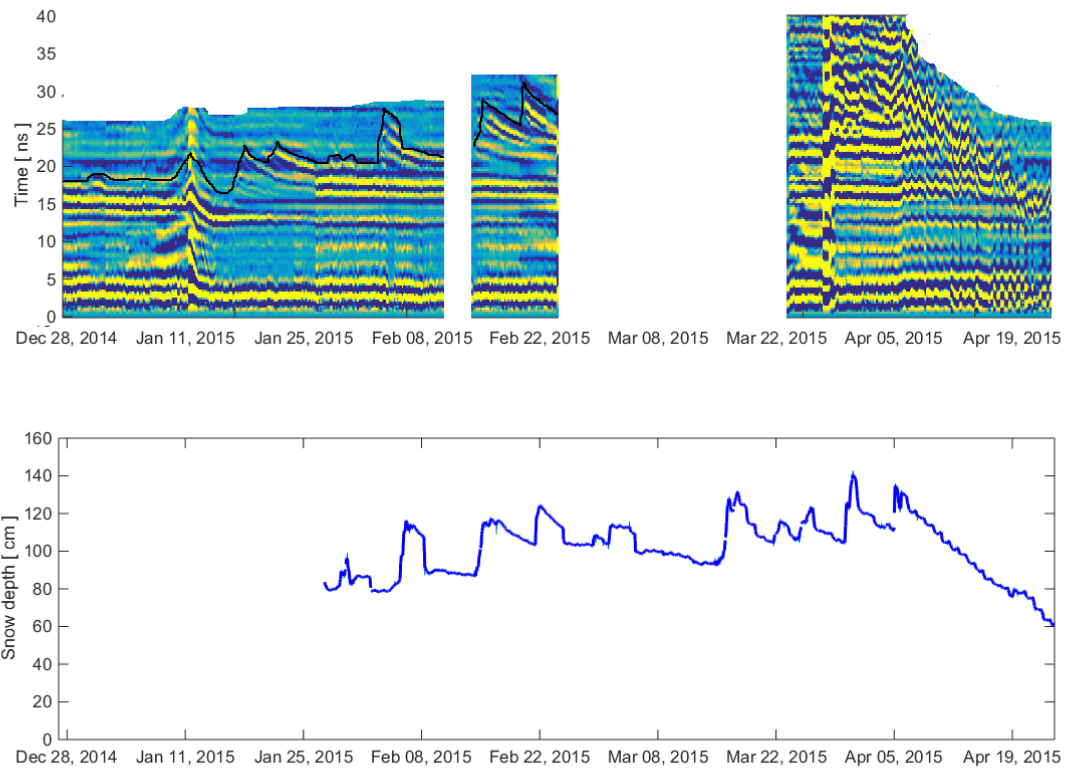


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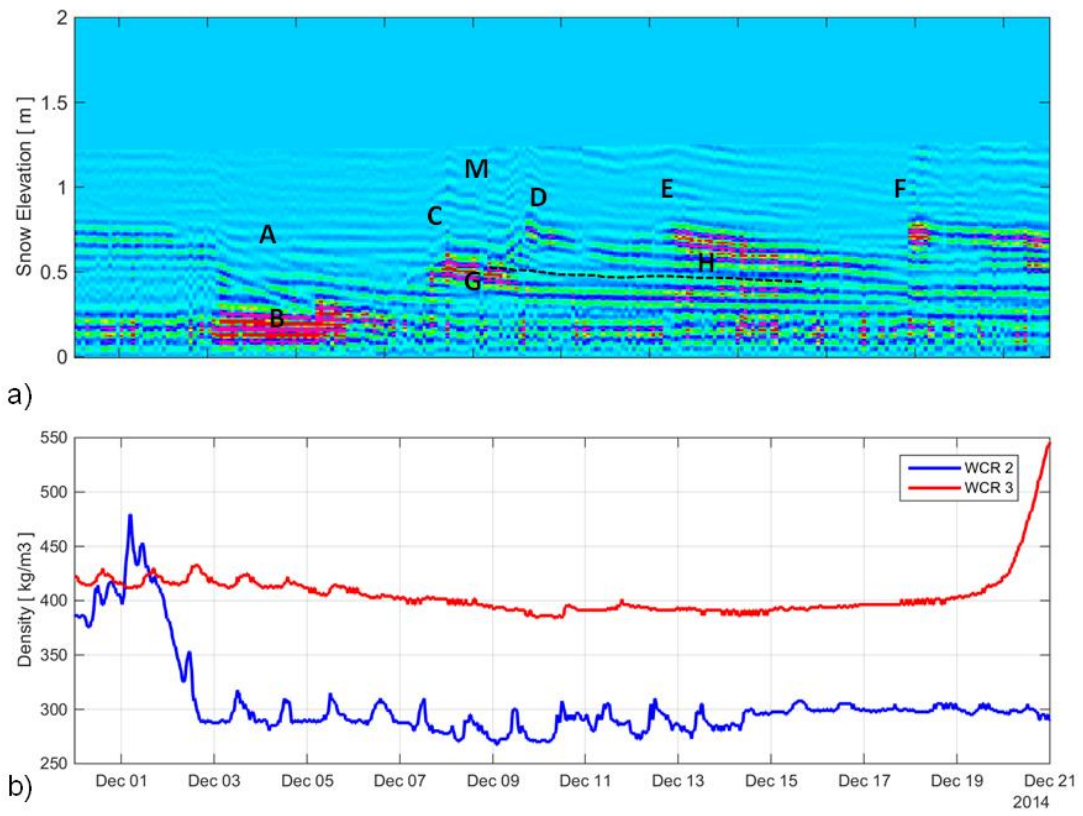


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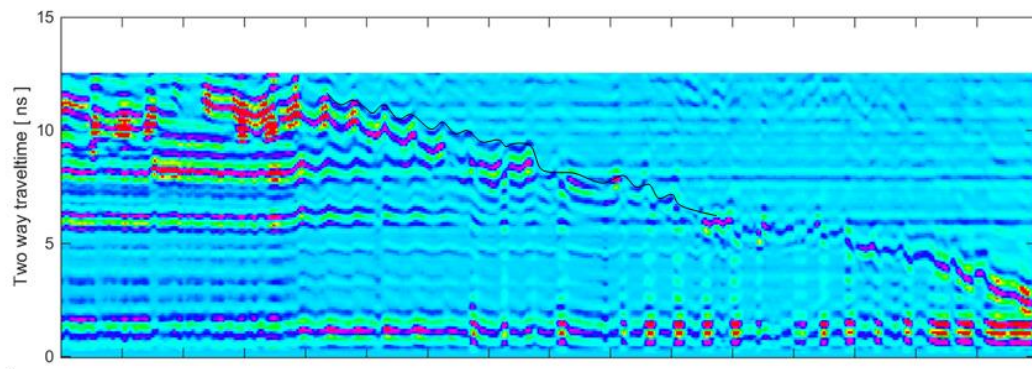
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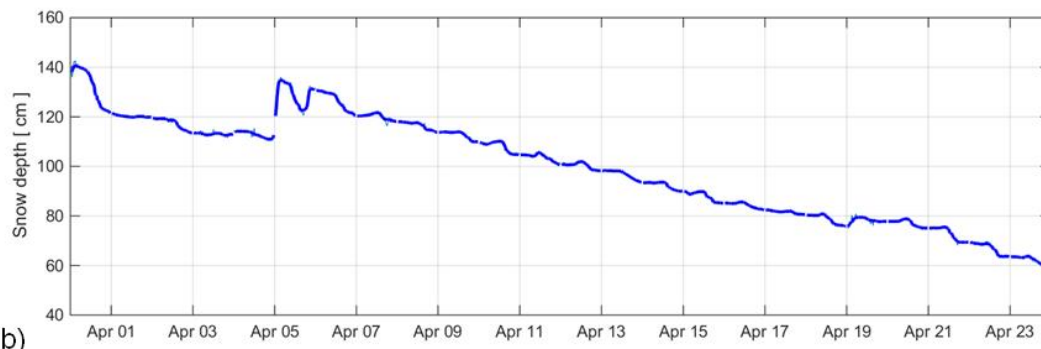
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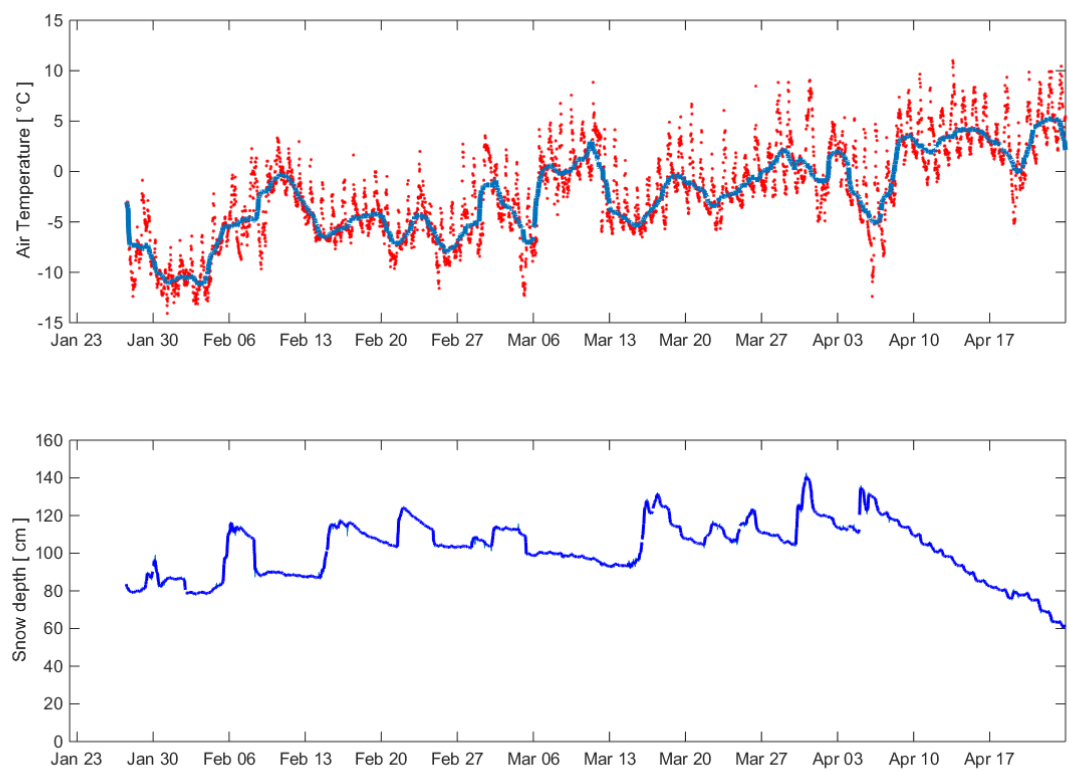


a)



b)

741
742 Figure 8
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745 Figure 9